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Perspective

Snakes in The Greenhouse: Does increased natural gas use reduce carbon dioxide emissions from coal consumption?

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ABSTRACT

Since natural gas emits less carbon than does coal per unit of electricity generation, some analysts suggest natural gas will help to mitigate climate change. However, sociological research has found that the substitution of one natural resource for another often does not happen as anticipated because of political and economic factors. Here, we analyze cross-national time-series data to examine the connection between growth in emissions from natural gas consumption and changes in emissions from coal use, controlling for several structural factors. We find that CO_2 emissions from natural gas sources do not displace CO_2 emissions from coal. These results cast doubt on whether the growing use of natural gas is likely to help substantially reduce CO_2 emissions.

1. Introduction

Natural gas produces lower carbon emissions than coal per unit of electricity generation [1]. Citing this fact, some policy-makers, energy analysts, and environmental scientists argue that increasing production of natural gas will suppress coal use and thereby help to curtail global climate change [2–4]. The development of hydraulic fracturing technologies has made shale gas resources more accessible and affordable, which has led natural gas to become a growing share of global electricity production [2,5]. However, a body of sociological research suggests that the substitution of one natural resource for another does not happen smoothly or reliably due to political and economic factors [6–8]. Despite this, little research has been done that examines the extent to which the increased use of natural gas suppresses CO_2 emissions from more carbon intensive sources, such as coal [9,10]. Here, we use cross-national time-series data to assess whether increases in emissions from natural gas consumption are associated with a decline in emissions from coal use, controlling for a variety of structural factors. We demonstrate that additional CO_2 emissions per capita from natural gas sources do not suppress CO_2 emissions from solid fossil fuel sources (e.g. coal). These results point to the importance of understanding political and economic factors that condition the effectiveness of new technologies in mitigating CO_2 emissions, and add to other research showing that the expansion of natural gas infrastructure is unlikely to reduce environmental impacts [9–11]. Ultimately, these results cast doubt on whether natural gas is an effective "bridge fuel" in global efforts to substantially reduce CO_2 emissions.

Social science research examining the effectiveness with which newly introduced technologies or resources, such as fuels, displace established ones has found that displacement does not typically occur as expected or intended, if, indeed, it occurs at all. This phenomenon – which has variously been termed the paperless office paradox [12,13] and the displacement paradox [6,14,15]– has been noted in the failure of the increasing presence of non-fossil energy sources to substantially suppress fossil fuel consumption [6]. Other research also has found evidence of a displacement paradox in sectors of industry such as agriculture [14], automobiles [15], communication and information technologies [12,13], and renewable energy [7,8]. In light of the findings from this body of research, the importance of examining the dynamics of displacement with regard to natural gas and coal use is clear.

Though the mechanisms through which such unexpected outcomes are manifested vary according to the particularities in each instance, in many cases such outcomes can be seen as a function of newly introduced technologies and resources being used in order to expand production and consumption [7]. The displacement paradox suggests that the forces driving the expansion of production are also effective at generating consumption to such an extent that new technologies and resources are used to satisfy new, rather than previously existing, industrial and consumer demands. Theoretical explanations of the displacement paradox focus on the power of corporations in market economies to drive growth so as to increase profits [7,8,18]. For instance, companies typically will work to 1) ensure that their products have markets, and to 2) expand consumption of all such products

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within those markets [14]. To put this differently, we should not necessarily expect a resource, or product, to simply replace another one, because in most arenas of economic enterprise the goal of the typical firm is to produce more products and increase the frequency with which all its products are consumed [17,18]. With respect to "green" technologies, this dynamic often has the consequence of preventing resources and technologies that are less environmentally harmful from *replacing* those that are more so. If, as it is often implicitly assumed is the case, demand for energy was more or less constant, then supplying energy from new sources would inevitably lead to a reduction in the consumption of established sources. However, the realities of sunk costs and geographic limitations can prevent new resources from replacing those that are extracted and distributed through well developed infrastructures, and in some instances can even spur the use of established resources [19]. Such a situation, which might be termed infrastructural path dependency, can lead to market expansion and the development of new social uses for an expanding energy supply [17,18].

In addition to theory on the displacement paradox, another complimentary socio-ecological approach, the green paradox [16], presents reasons why supply-side forces generate demand. The green paradox and displacement paradox together highlight how broader political and economic context may influence the extent to which one resource is able (or not) to effectively displace another. The displacement paradox emphasizes that new products, technologies, and resources often serve to expand consumer markets, rather than replacing resources previously used in such markets. Complimenting this view, the green paradox offers insight into how regulation and market mechanisms intended to curb the use of a particular resource might unintentionally lead to an intensification of its use. The green paradox theorization starts with the observation that businesses typically seek to avoid regulations and work to prevent loss of profits from the devaluation of their own capital assets, such as control of fossil fuel reserves. Resource-owning firms anticipate the introduction of regulations that may reduce the value of their assets – such as new environmental laws that could increase the costs of extracting, and/or lower the profit margins for selling, fossil fuels. For instance, policy implementation and government subsidization aimed at encouraging the production of wind power are likely to have the intended effect of driving down the market price of wind power, but this will also suppress the price of other energy sources in a competitive market. This brings about the unintended consequence of motivating firms to anticipate future government actions and extract and sell as much of the established resources – fossil fuels most notably – as quickly as possible *before* new regulations or subsidies are implemented that drive down prices or prevent the firms from accessing or selling these resources. Thus, the paradox is that the anticipation of new environmental laws aimed at suppressing the use of fossil fuels drives the expansion of fossil fuel consumption [16,19]. The green paradox fits with the displacement paradox in that it shows how supply-side logics drive resource use and can prevent new technologies and resources from suppressing the use of established ones.

We argue that by using these theoretical approaches as our lens, we are able to understand that – though the introduction of new technologies, resources and policies will likely always have many unintended consequences, and thus the outcomes of their introduction will continue to evade accurate prediction– in the socio-economic context of the contemporary global economy, market mechanisms will often result in new resources being used *in addition to,* rather than *in place of,* previously established ones. Therefore, we question whether it is wise to expect natural gas production to dramatically suppress coal use. This is an especially important issue considering the central role of natural gas resources in discussions of energy transitions and global climate change. Recent estimates project that global natural gas consumption will increase by 43% between 2015 and 2040 [20]. To this end, the U.S. Department of Energy has approved increases in the export of liquid natural gas from roughly 28.48 billion cubic feet/day in 2016 [21] to 54.98 billion cubic feet/day by 2050 [22]. Further, as noted above, some scholars and analysts have suggested that increasing reliance on natural gas use presents market-based opportunities for economic growth, the mitigation of emissions, and establishing a pathway to greater reliance on renewable fuel sources [23]. In order to explore whether or not such increases in the worldwide use of natural gas will aid in the mitigation of CO_2 emissions, or whether increasing natural gas use presents yet another instance of the displacement paradox, we perform a series of statistical analyses that explore whether or not the use of natural gas suppresses coal use.

2. Data and methods

In order to test for the displacement of CO_2 emissions from the consumption of solid fossil fuel sources (coal) by those from consumption of natural gas sources, we estimate five fixed-effects panel regression models using World Bank [24] data on all nations for which they are available for all years for which they are available in the range from 1960 to 2013. Each model examines the effect of generating an additional kilogram of CO_2 per capita from natural gas consumption on the level of CO_2 per capita (kg) emitted from the consumption of coal, while controlling for a variety of structural factors that are known to be drivers of emissions. We note that, though there are a number of well-established ways to explore the relationships between human action and environmental impact, including using elasticity models like STIRPAT [25], to test for displacement requires a specific model structure. Since we are interested in determining how many units of CO_2 emissions from coal sources are displaced by each unit of CO_2 emitted from natural gas, it is necessary to measure emissions in original units rather than use the logarithmic structure of STIRPAT.

In order to account for the variety of forces driving energy use and emissions, we control for a number of factors established in previous research as key influences on emissions. These include: electricity consumption per capita measured in 1000 s of kilowatt hours (kWh), since a major use of coal and natural gas is for electricity generation; the percentage of the population living in areas classified as urban, since urbanized nations have been found to typically have higher CO_2 emissions than less urbanized nations; GDP per capita (measured in 1000 s of inflation adjusted US$), which is incorporated to account for the effects of economic activity, a central driver of energy use and emissions; the quadratic of GDP per capita, which we include in order to allow for a non-linear relationship between economic activity and coal-based emissions; the percentage of GDP derived from manufacturing activities, as such activities have been shown to be the most carbon intensive; the percentage of the population that is of a working age (15–64), since the working age population engages in higher levels of production and consumption than other age groups; and per capita CO_2 emissions from liquid fuels (i.e., oil), since this is the major fossil fuel source other than coal and gas.

Taking the nation-year as our unit of analysis, we develop fixed-effect panel regression models with robust standard errors that correct for clustering of residuals by nation (specifically, we used the "xtreg" command in STATA 14 with the "fe" and "robust" options). We include fixed-effects estimators for both nation and period. We estimate period effects by including dummy variables for each year in our models. Using this approach allows our models to control for effects that are constant throughout time but vary across nations (e.g. geographic differences), as well as factors that affect all nations equally but change over time (e.g. fluctuations in the international price of fuels). The general form of the model is:

$$\text{Coal emissions}_{it} = \beta_0 + \beta_1(\text{Natural gas emissions}_{it}) + \beta_2(\text{Percent urban}_{it}) + \beta_3(\text{Electicity consumption}_{it}) + \beta_4(\text{GDP per capita}_{it}) + \beta_5(\text{GDP per capita}^2{}_{it}) + \beta_6(\text{Age dependency ratio}_{it}) + \beta_7(\text{Liquid fuel emissions}_{it}) + \beta_8(\text{year 1961}_t)\ldots + \beta_{60}(\text{year 2013}_t) + u_i + e_{it}$$

Where "Coal emissions$_{it}$" represents kilograms per capita of emissions from solid fuel source consumption for nation i in year t; "Natural gas emissions$_{it}$" indicates the kilograms of CO_2 emissions from natural gas consumption per capita for nation i in year t; "Electricity consumption$_{it}$" indicates the kilowatt hours per capita of electric consumption during time t in country i; "GDP per capita" indicates the value of the GDP per capita in country i during year t; "GDP per capita$^2_{it}$" indicates the value of GDP per capita squared in country i during year t; "Percent urban$_{it}$ " is the percentage of the population residing in urban areas of nation i in time t; "Age dependency ratio$_{it}$" is the proportion of the population that is between 15 and 64 years of age in nation i during time t; "Liquid fuel emissions$_{it}$" is the CO_2 (kg) per capita emitted from liquid fuel consumption in nation i in year t; "year$_t$" is a binary dummy variable for each year; u_i is a control for nation specific effects; and e_{it} is the stochastic residual term for nation i in period t.

All data for the present analyses were drawn from the World Bank's *World Development Indicators* database [24]. Our analyses include data for all nations for which they are available from 1960 to 2013. We note that the World Bank [24] treats Macao, Hong Kong, and China as separate units for data recording purposes. Consequently, they are treated as separate units in our analyses as well. In all models we report statistical significance (two-tailed tests) relative to 0 for the β coefficients for all variables, and relative to −1 for only the natural gas variable, since that value would indicate unitary displacement (see below).

We note two hypothesized values for the degree to which natural gas emissions might be displacing those from coal that are particularly meaningful. First, it is possible that natural gas *energy* is displacing coal-based *energy* on a one-for-one basis (e.g., each kWh of energy from natural gas-based consumption leads to one less kWh of energy from coal-based consumption). If this is the case then we should expect to see a displacement coefficient of roughly −1.79, as coal emits 1.79 times as many kilograms of CO_2 as natural gas per unit of energy released through combustion [1]. Any value less than −1 indicates that the addition of natural gas leads to an overall reduction in emissions (controlling for the effects of other factors). The second, alternative, hypothesized value is −1, which would indicate that CO_2 emissions from coal consumption decline in equal proportion to those added by natural gas (unitary displacement of emissions). This would indicate that adding natural gas is associated with rising energy consumption, but due to the lower carbon content of natural gas relative to coal, CO_2 emissions balance out. A displacement coefficient between −1 and 0 indicates that natural gas-based emissions only partially displace emissions from coal, and therefore adding natural gas will contribute to rising total emissions. Further, if the displacement coefficient is not significantly different than 0, then this suggests that CO_2 emissions from natural gas consumption have no effect on coal use and are simply added to, rather than emitted in place of, CO_2 emissions from coal. A positive value would indicate that the use of natural gas spurs the use of coal, rather than suppressing it.

3. Results and discussion

The results from our analyses can be found in Tables 1 and 2. Model 1 (Table 1) includes basic controls for energy demand at the national level: urbanization, the age-dependency ratio, and GDP per capita (including its quadratic to allow for non-linearity). The Model 1 coefficient of −0.013 for natural gas is significantly different from −1, and is not significantly different than 0, which indicates that emissions from natural gas consumption have no displacement effect on emissions from coal.

Models 2 and 3 control for the same drivers of energy demand that are included in Model 1. However, both models also include a control for electricity consumption per capita, and Model 3 includes CO_2 emissions per capita from consumption of liquid fossil fuel sources as well. Displacement coefficient estimates in Models 2 and 3 are consistent with those in Model 1, meaning they indicate that emissions from natural gas do not result in a significant reduction of emissions from coal.

An important methodological limitation of the current study is that in many nation-years there are no emissions from coal consumption, and therefore no emissions to be displaced. One way to address this issue is to use a tobit model, conceptualizing the dependent variable as left censored at the value of 0. A major problem with this approach, however, is that there is not an unbiased fixed-effects estimator for

Table 1
Displacement effect of natural gas CO_2 emissions on coal CO_2 emissions in fixed effects panel regression models with robust standard errors.

	Model 1 Coef. (S.E.)	Model 2 Coef. (S.E.)	Model 3 Coef. (S.E.)
Natural gas electricity emissions per capita	$-0.013^{\dagger}$ (0.010)	$-0.024^{\dagger}$ (0.014)	$-0.022^{\dagger}$ (0.014)
Liquid fuel electricity emissions per capita	–	–	−0.021 (0.030)
Electricity consumption per capita	–	0.055 (0.038)	0.055 (0.038)
Manufacturing (% of GDP)	0.009 (0.005)	0.010 (0.006)	0.010 (0.010)
Age Dependency Ratio	−0.004 (0.002)	−0.006 (0.003)	−0.006 (0.004)
GDP per capita	0.067^{*} (0.026)	0.069^{**} (0.023)	0.068^{**} (0.022)
GDP per capita^2	-0.001^{**} (0.000)	-0.001^{***} (0.000)	-0.001^{***} (0.000)
Urbanization	0.021^{*} (0.009)	0.032^{**} (0.012)	0.033^{**} (0.012)
Nations	176	131	131
Nation-Years	5232	3699	3695

Note: These results are based on analyses of all nations with available data from 1960 to 2013. All models include year-dummies that are not shown. The coefficient for the natural gas variable represents the estimated change in the emission of carbon dioxide (kg) per capita from the consumption of solid fossil fuel sources (i.e. coal) for every additional kilogram of CO_2 emitted by from the consumption of natural gas.

† Significantly different from −1 at the 0.001 alpha level (two-tailed test). (Shown only for natural gas).

* Significantly different from 0 at the 0.05 alpha level (two-tailed test).

** Significantly different from 0 at the 0.01 alpha level (two-tailed test).

*** Significantly different from 0 at the 0.001 alpha level (two-tailed test).

Table 2
Displacement effect of natural gas CO_2 emissions on coal CO_2 emissions in nations with non-zero (Model 4) and high (Model 5) emissions from coal electricity production in fixed effects panel regression models with robust standard errors.

	Model 4 Coef. (S.E.)	Model 5 Coef. (S.E.)
Natural gas electricity emissions per capita	$-0.002^{\dagger}$ (0.109)	$0.318^{\dagger}$ (0.218)
Liquid fuel emissions per capita	0.012 (0.051)	−0.096 (0.136)
Electricity consumption per capita	0.069 (0.060)	0.038 (0.047)
Manufacturing (% of GDP)	0.011 (0.007)	0.035 (0.024)
Age Dependency Ratio	−0.005 (0.005)	−0.025 (0.024)
GDP per capita	0.072^{*} (0.028)	0.141^{*} (0.064)
GDP per capita^2	-0.001^{**} (0.000)	-0.002^{**} (0.001)
Urbanization	0.039^{**} (0.014)	0.081^{**} (0.026)
Nations	114	50
Nation-Years	2862	1004

Note: These results are based on analyses of all nations with available data from 1960 to 2013. Both models include year-dummies that are not shown. The coefficient for the natural gas variable represents the estimated change in the emission of carbon dioxide (kg) per capita from the consumption of solid fossil fuel sources (i.e. coal) for every additional kilogram of CO_2 emitted by from the consumption of natural gas. Model 4 includes only those nation-years with more than 0 emissions from solid fossil fuel sources. Model 5 includes only those nation-years that emit greater than the mean of coal source emissions in the sample of nations from Model 1.

†Significantly different from −1 at the 0.001 alpha level (two-tailed test). (Shown only for natural gas).

*Significantly different from 0 at the 0.05 alpha level (two-tailed test).

**Significantly different from 0 at the 0.01 alpha level (two-tailed test).

panel tobit models. Nonetheless, we estimated tobit models with and without fixed-effects estimators and present these in the supplementary material (Supplementary Table S1). The results of these models suggest similar conclusions to those we present here (i.e., emissions from natural gas are not displacing those from coal).

As an alternative strategy to address this limitation, we estimate a series of models in which the analysis is limited to nations that do have emissions from the consumption of solid fossil fuel sources. These results are presented in Table 2. In Model 4 we included all controls and limited our analysis to those instances where emissions from solid fossil fuel sources were greater than 0. In Model 4 the displacement coefficient remains consistent with those estimated in Models 1–3. Finally, in Model 5 our analysis is limited to only those cases with substantial emissions from solid fossil fuel sources, which we define as nations with emissions greater than the mean of CO_2 emissions from such sources in Model 1 (.987 kg per capita). As with all other models, the displacement coefficient estimated in Model 5 suggests that increased CO_2 emissions from natural gas consumption do not suppress those from coal (the coefficient is, in fact, *positive,* although not significantly different from 0).

In order to ensure that results are not being driven by nations with historically low electricity consumption using both coal and natural gas in order to fulfill unmet energy needs, we explored alternative models. We divided the sample into cases in the lower 50th percentile of electricity consumption per capita, and into those in the upper 50th percentile of electricity consumption per capita, and estimated a separate model (equivalent to Model 3) for each half. The results of these analyses, which are presented in the supplementary material (Supplementary Table S2), are consistent with the results from the models that include all observations. As an additional robustness check, we ran an alternative model where only nation-years with electricity consumption per capita between the 10th and 90th percentile of the distribution were included in the sample. The results of these models, which are presented in Supplementary Table S2, did not differ in any notable way from those presented here.

Our results suggest that expansion of natural gas use is not an effective means of mitigating emissions. Though we cannot confirm them in this analysis, there are a number of potential reasons for this. For instance, it is possible that in the electrical sector, rather than replacing electricity produced from coal, natural gas electricity is displacing established non-fossil fuel electricity sources, such as hydro or nuclear [8]. In addition, the findings here indicate that, even though increasing use of natural gas has, in principle, the potential to reduce environmental impact if the technology is properly deployed, currently the increasing use of natural gas is likely a result of market expansion and not suggestive of reductions in environmental impact. In this regard, the present study demonstrates the displacement paradox, showing that the introduction of a new resource does not necessarily suppress the use of well-established ones. We note that the green paradox also offers a potential explanation for this phenomenon. The threat of regulations aimed at reducing the use of coal may have inadvertently increased coal production in the short term as coal companies worked to make profits before environmental laws restricted their ability to do so. Further, environmental protection policies aimed at natural gas extraction may have incentivized natural gas producers to increase extraction in the short term (increasing total electricity production in the short term). In both of these scenarios, the displacement of coal by natural gas would be offset.

Our findings suggest that if greenhouse gas emissions are to be mitigated, an important step will likely be implementing policies that ensure that cleaner technologies and resources are used to *replace* more polluting ones and are not simply added to them [6–10]. To this end, it could be beneficial to orient energy transition policies around discouraging the use of more carbon intensive fuels, rather than subsidizing the use of less carbon intensive ones. Findings also suggest that caution might be warranted in attempting to stimulate economic growth by way of expanding the market for natural gas fuel sources. Previous research has noted that, even if displacement occurred in the straightforward manner it is often expected to, much of the current natural gas reserves will need to remain unutilized in order to keep global average temperature changes below a critical range [26,27]. The findings presented here suggest that, at least in the period 1960–2013, natural gas has not been used in a manner that leads to the displacement of coal fuel sources globally. Therefore, the prospect that natural gas fuels will be an effective tool in the mitigation of CO_2 emissions absent the inclusion of additional regulatory policy seems all the more unlikely. In the broadest sense, this research suggests that, though technical improvements are likely a necessary aspect of climate change mitigation, on their own they are not a sufficient one, and we must consider the political, social and economic contexts in which new resources and technologies are being deployed, as well as how such contexts might encourage actors to respond in a way that prevents these tools from having their intended effects. Though we have approached the question of how effectively natural gas resources are replacing coal resources at the macro level using regression analyses, we note that the importance of this question requires researchers to investigate such relationships on multiple scales, and in a variety of more specified social, economic, and political contexts [25]. To that end, it is our hope that research in the Coupled Human and Natural Systems (CHANS) and Socio-ecological Systems (SES) traditions will further explore the barriers to effectively replacing older resources with newer ones.

Conflict of interest

The authors declare no conflict of interest related to this study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.erss.2018.02.001.

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